DARPA/NSF Virtual Integrated Prototyping Review
August 14-16, 2000, San Francisco, CA

Can interface roughness be useful in devices ?

David Ting

**JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY**

August 15, 2000

Acknowledgement

Collaborators

- Infrared Focal Plane Array Technology Group, JPL
  - Sumith Bandara
  - Sarath Gunapala
  - John Liu
  - Jason Mumolo
  - Sir Rafol

- Dept. of Mathematics, UCLA
  - Ming Gu

Sponsors

National Aeronautics and Space Administration, breakthrough sensor & instrument component technology thrust area of the cross enterprise technology development program.

Defense Advanced Research Projects Agency, Virtual Integrated Prototyping.

Outline

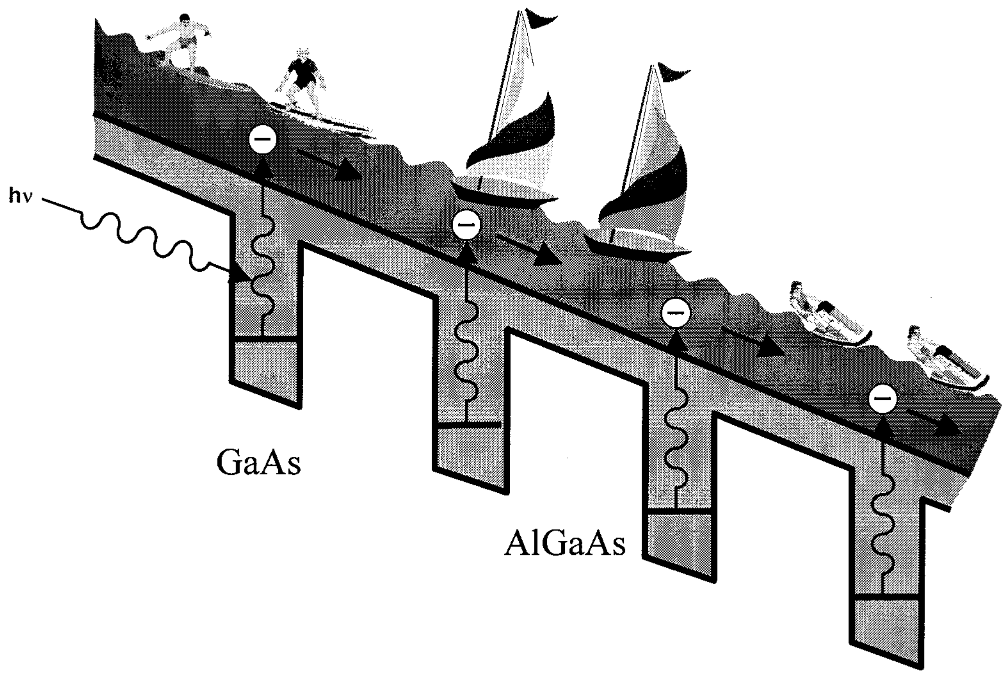
- Motivation and Background:
  - Quantum Well Infrared Photodetectors (QWIP): Advantages and Disadvantages
- Using concepts from interface roughness studies to make a better intersubband detector:
  - Island Insertion Infrared Detector (I^3D)
- Preliminary Results and Discussions
  - What's needed.

Motivation

- Interface roughness typically degrades device performance.
  - Lower peak-to-valley ratio in resonant tunneling diodes

- Can interface roughness be useful ?
  - Motivated by problems encountered in quantum well infrared photodetector (QWIP) research.
  - Concepts from interface roughness studies may provide a solution.

Introduction to Quantum Well Infrared Photodetector (QWIP)



- Tailor quantum well structures to obtained desired intersuband levels for specific infrared wavelengths.

Advantages of QWIP

- Temporal stability due to low 1/f noise.
  - 1/f noise knee ~ 30 mHz (30 Hz in MCT) for 9-10 μm .
- Spatial uniformity enables large format focal plane arrays.
  - Typical operability > 99.9%
- Highly tailorable spectral response.
  - Narrow band, broad band, multicolor.
  - GaAs/AlGaAs 5.6 - 20 μm and beyond.
  - InP/InGaAs/InAlAs for shorter wavelengths.
- High yield due to mature GaAs technology
  - Low cost. Fast turnaround.

Main Disadvantage of QWIP

Poor light coupling results in

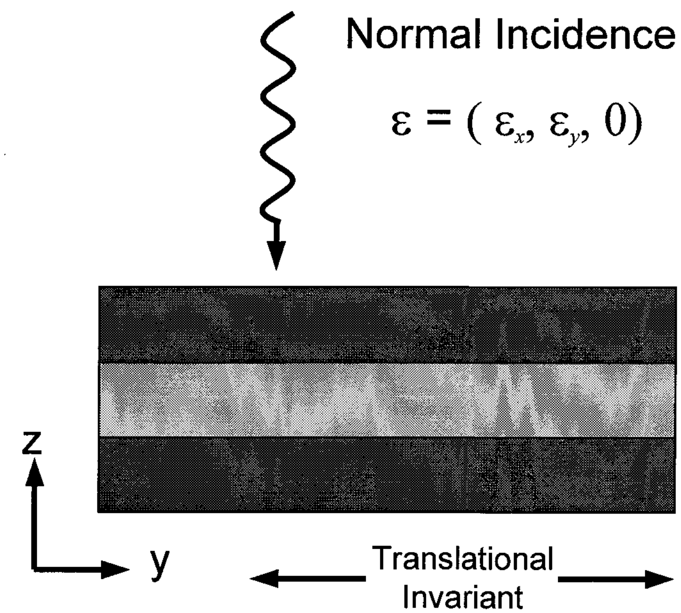
low quantum efficiency.

- Low absorption quantum efficiency
  - Typical absorption QE ~ 15% - 30%
  - Net QE ~ 3% - 10%
- No (very small) normal incidence radiation absorption for inter conduction subband transitions.
- Uses grating structures for light coupling.

The Normal Incidence Problem

- Oscillator Strength: $f_{12} \propto |\langle\psi_1|\varepsilon\cdot\mathbf{p}|\psi_2\rangle|^2 \propto$ $|\langle\psi_1|\ \varepsilon_x(\partial/\partial x) + \varepsilon_y(\partial/\partial y) + \varepsilon_z(\partial/\partial z)\ |\psi_2\rangle|^2$
- Envelope Functions have no variations in lateral (x,y) directions.
- Normal Incidence: $\varepsilon = (\ \varepsilon_x, \varepsilon_y, 0)$

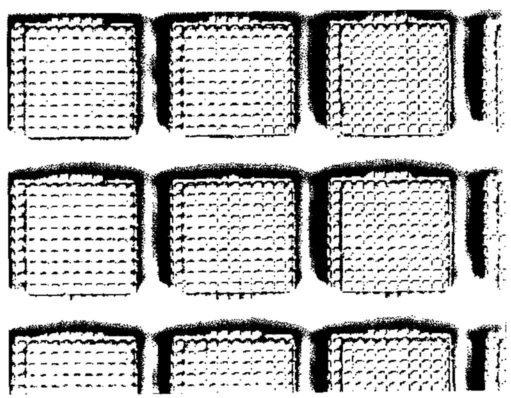
No oscillator strength for normal incidence radiation !

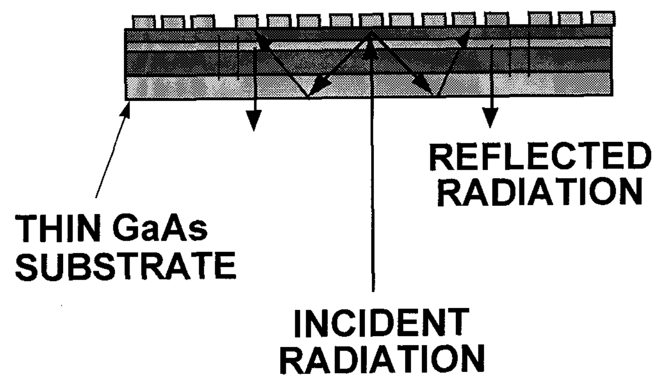


Solutions to the Normal Incidence Problem

- Oscillator Strength: $f_{12} \propto |\langle\psi_1|\varepsilon\cdot\mathbf{p}|\psi_2\rangle|^2$

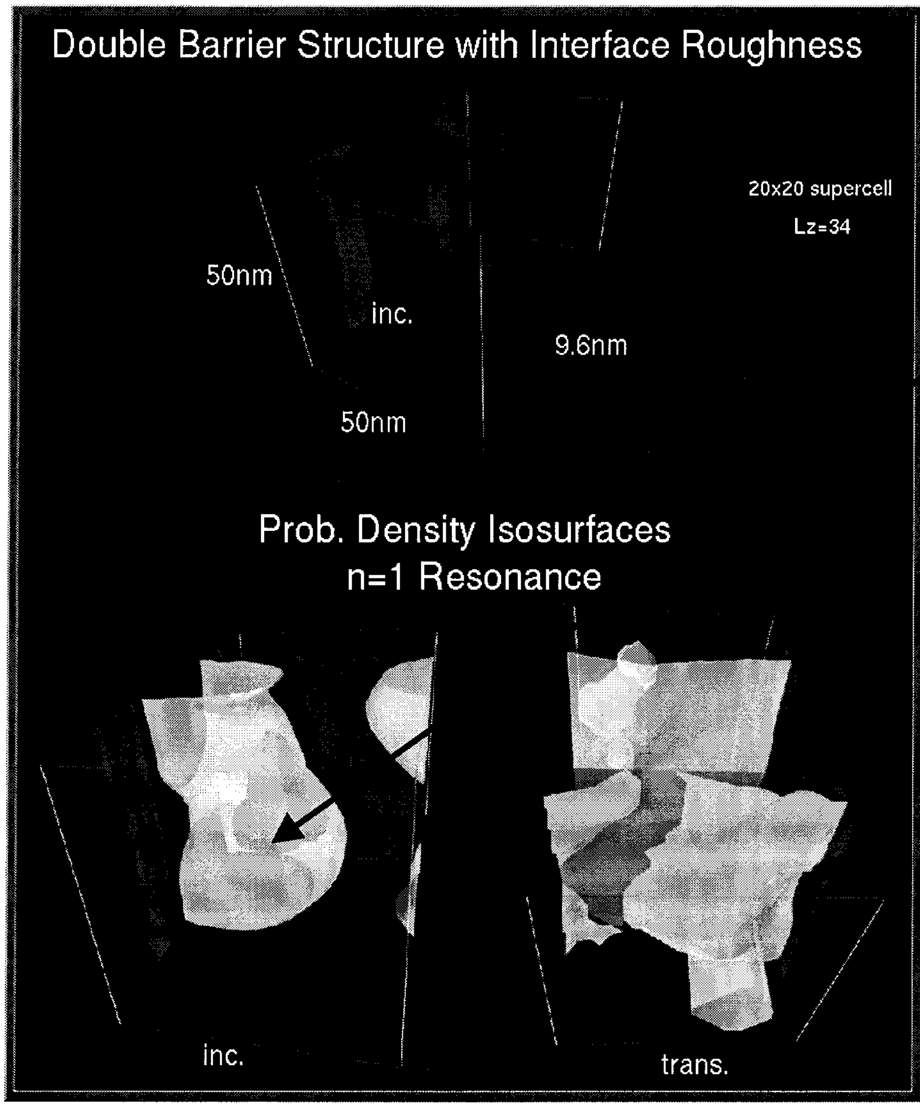
- Current solution: Introduce grating structures to change direction of light.



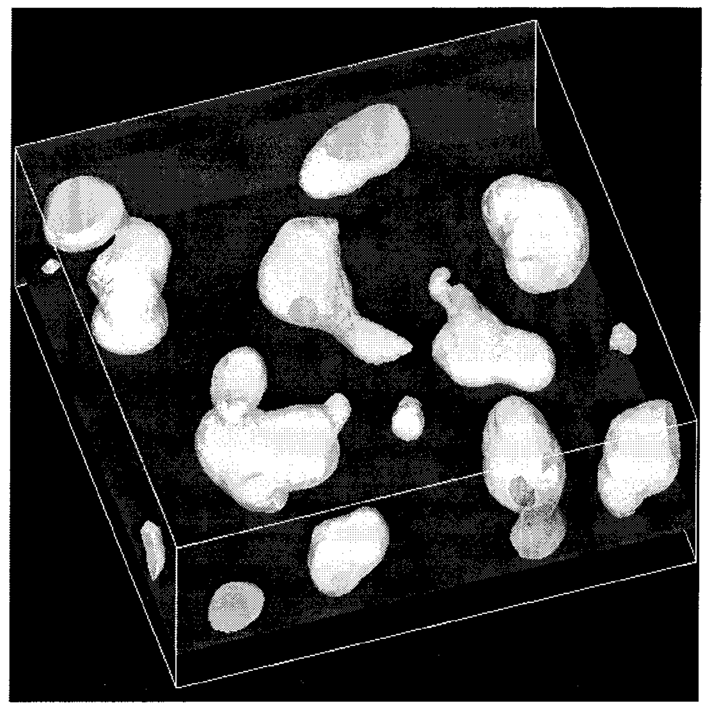


- A Complementary solution: Introduce lateral variations in the envelope functions.

Perturbing Quantum Well Wave Functions: Lessons from Interface Roughness Studies

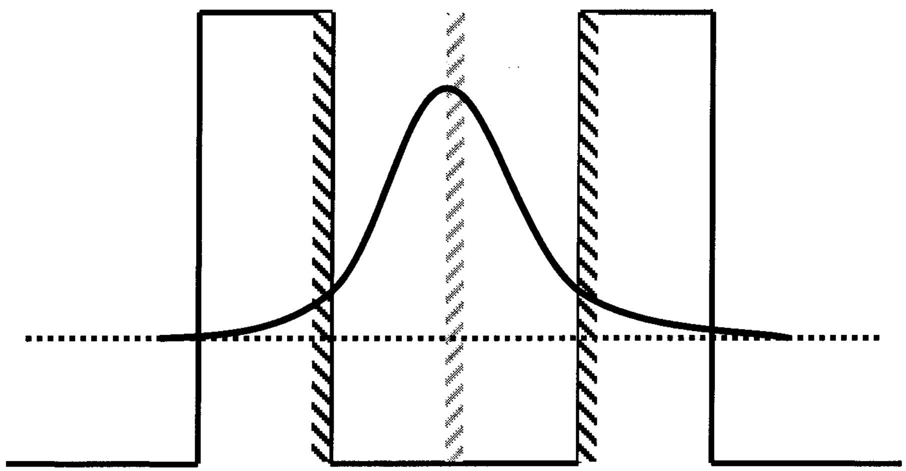


- Study of interface roughness effects in double barrier resonant tunneling diodes found interface roughness can induce localization of resonant state wave functions, provided island sizes are sufficiently large. [D. Z.-Y. Ting, S. K. Kirby and T. C. McGill, Appl. Phys. Lett. **64**, 2004 (1994)]

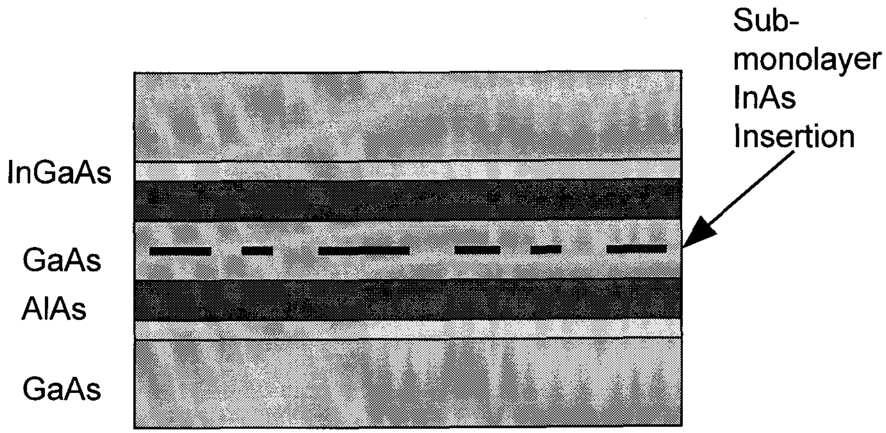


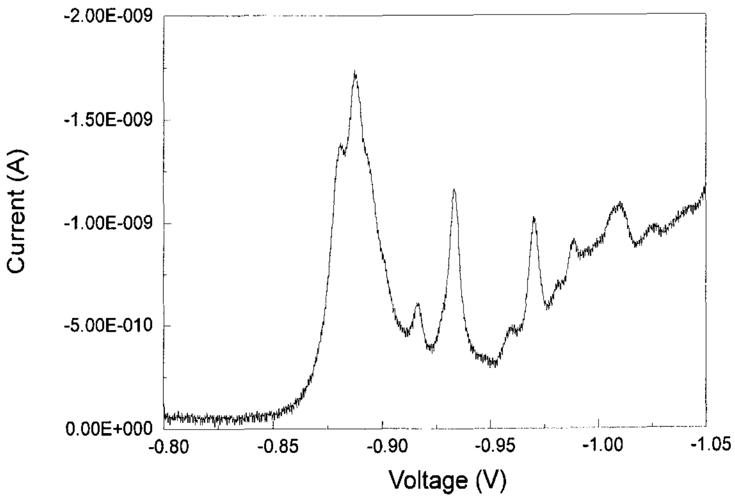
Enhancing Interface Roughness Scattering

- Probability density is relatively small at the interfaces.
- Could enhance localization effects by introducing roughness in the middle of the quantum well where probability density is highest.
- How ?



Double Barrier Structures with Mid-Well Island Insertion





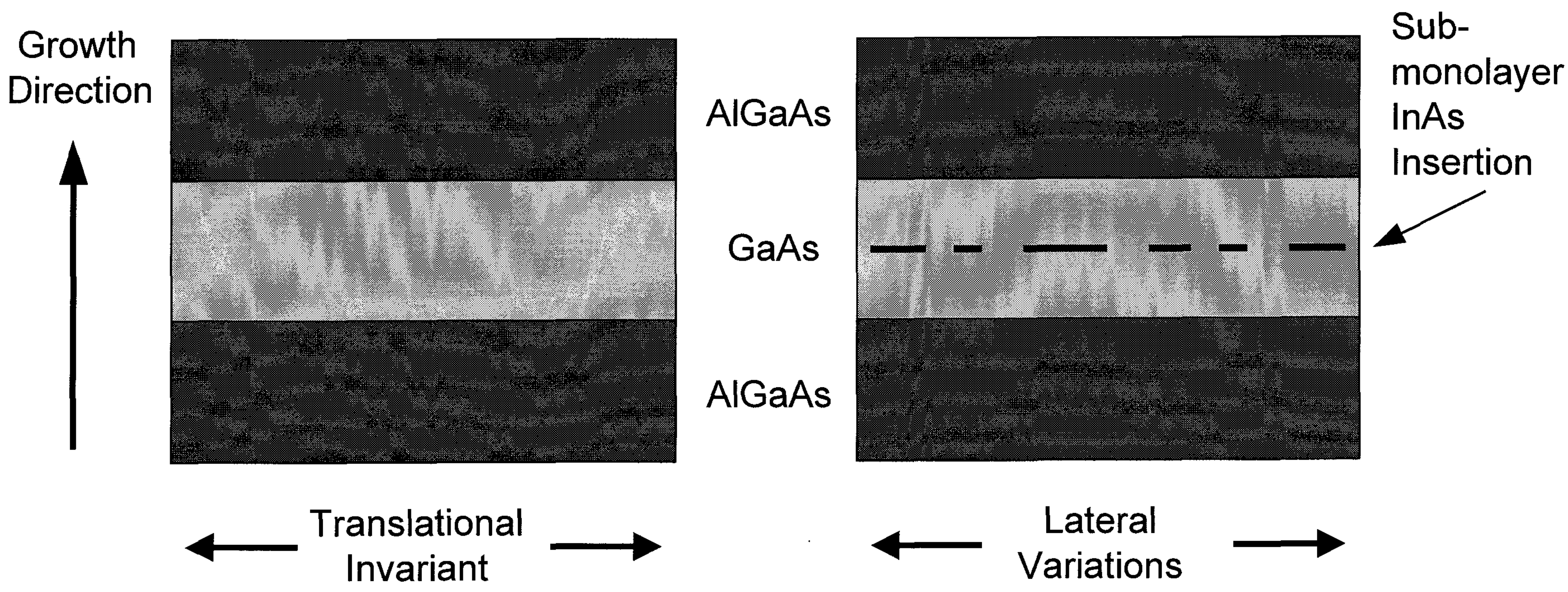
- GaAs/AlAs DBRTD with 1/8 monolayer InAs insertion and InGaAs emitter.
- Measurements showed series of resonance attributed to self-organized InAs island formation.
- In agreement with modeling results.

[J. N. Wang, R. G. Li, Y. Q. Wang, W. K. Ge, and D. Z.-Y. Ting, *Microelectronic Engineering*, **43** 341-347 (1998).]

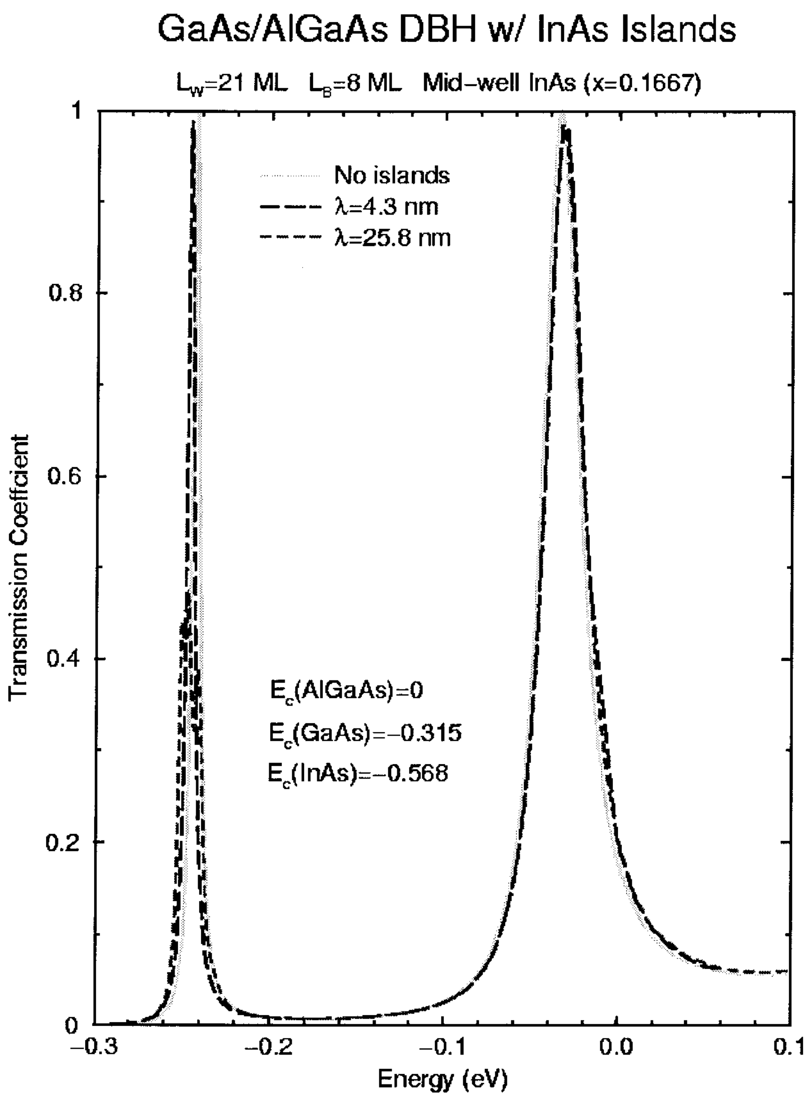
QWIP vs. I^{3}D

Quantum Well Infrared Photodetector

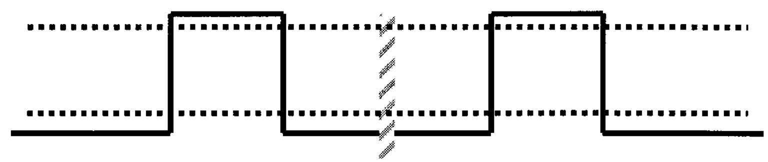
Island Insertion Infrared Detector



Modeling GaAs Quantum Well with InAs Island Insertion



- Model system:
  - GaAs/AlGaAs QW with 2 levels.
  - 1/6 ML InAs insertion at mid-well.
  - ΔE_C(GaAs,InAs) = 0.5 eV
  - Varying island sizes
  - Model DBH. L_W= 5.9 nm L_B=2.3 nm. Quantized levels show up as resonances in transmission spectrum
  - 3D supercell calculation. 64 nm x 64 nm repeating cells in in-plane directions.
- Numerical acceleration provided by UCLA (Ming Gu Group).

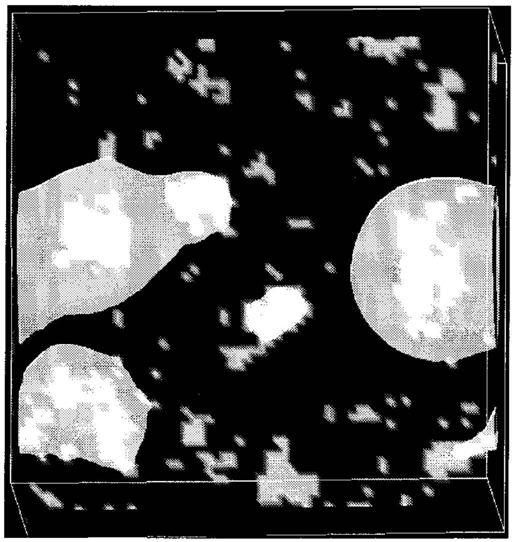


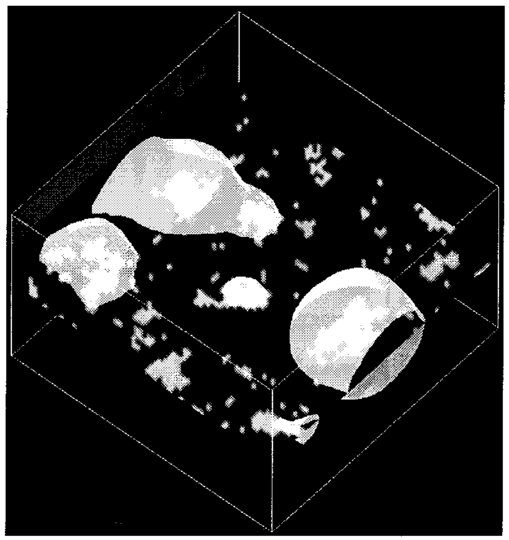
- Spectra similar to pure QW spectrum.
- Slight down shift of n=1 level; up shift of the n=2 level.

Ground State Wave Function: Lateral Variations

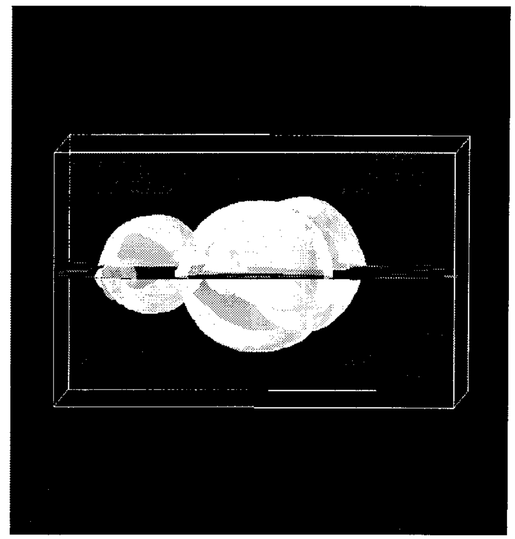
- Structure indicated by colored surfaces (AlAs, GaAs, InAs).
- Isosurfaces of probability density shown as translucent surfaces.
- Scale in growth direction expanded (3.54x).
- Wave function of localized states in large islands (λ=9.8 nm) structures show significant in-plane variations.
- Localization over islands.

Top View

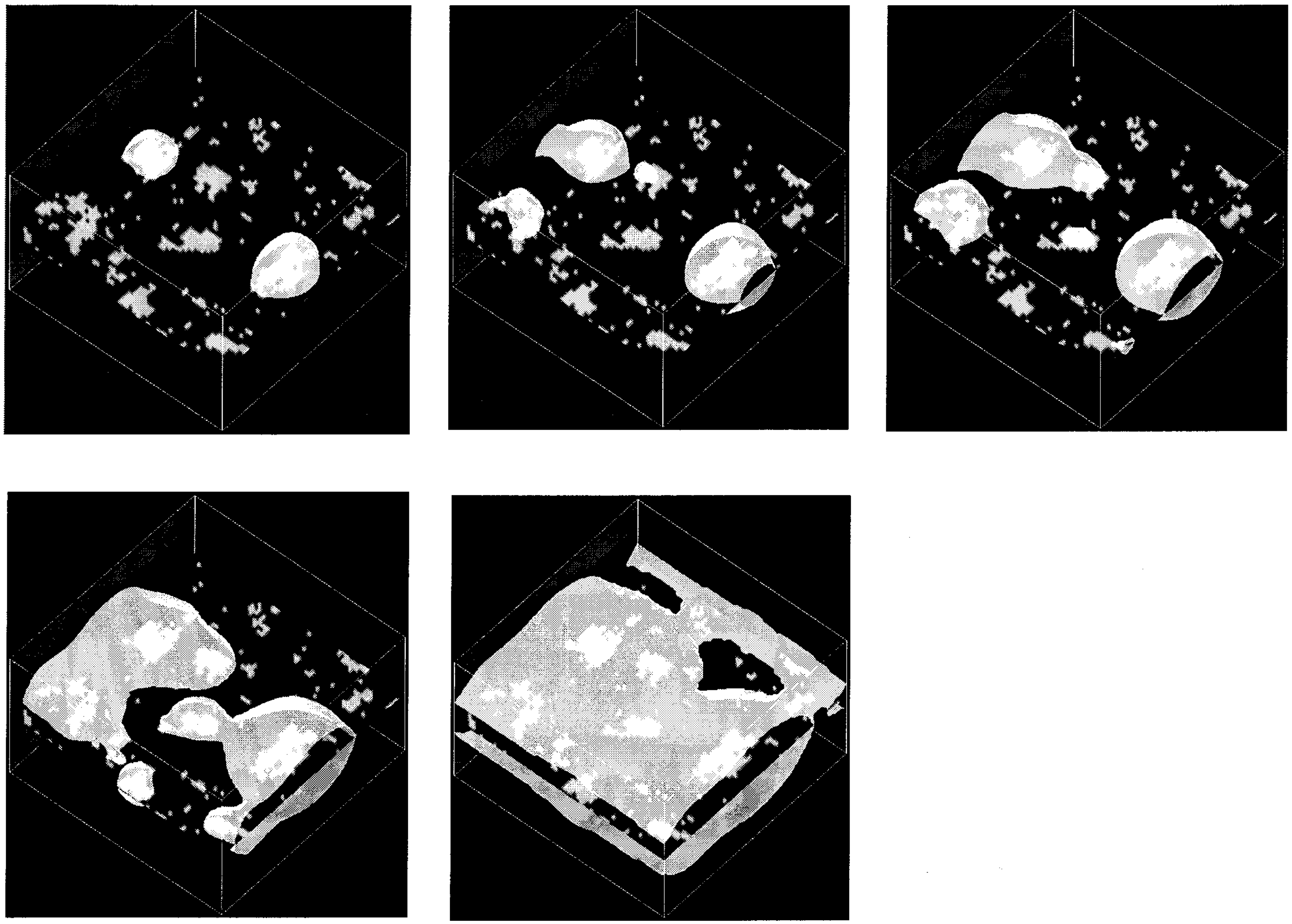




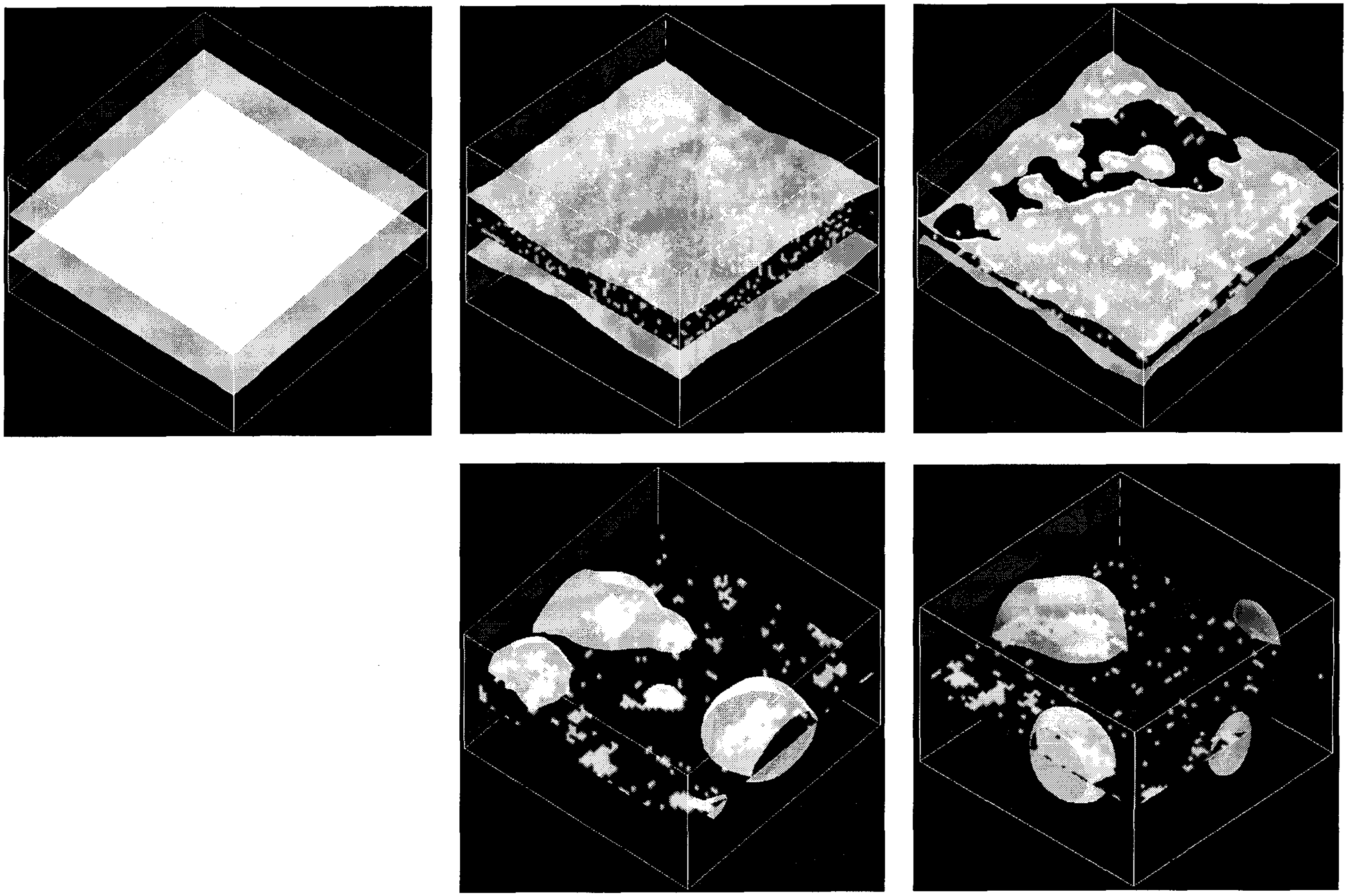
Side View



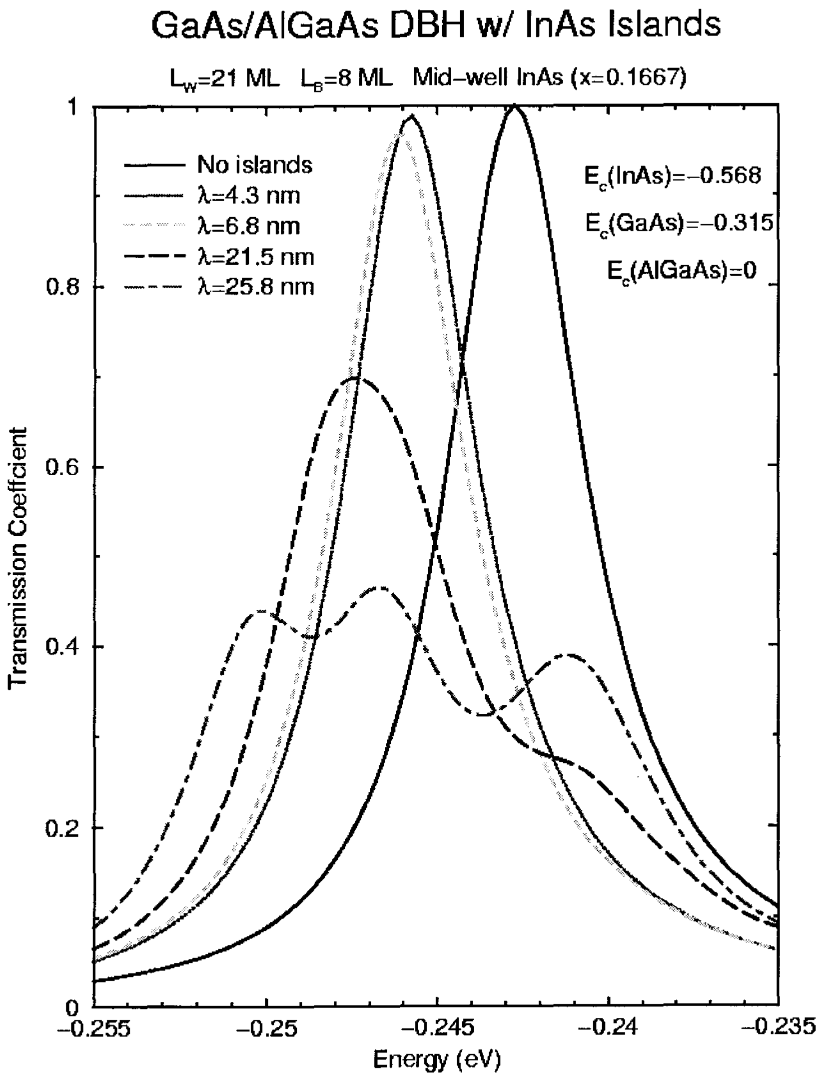
Ground State Wave Function: Different Contour Levels



Ground State Wave Function: Dependence on Island Size

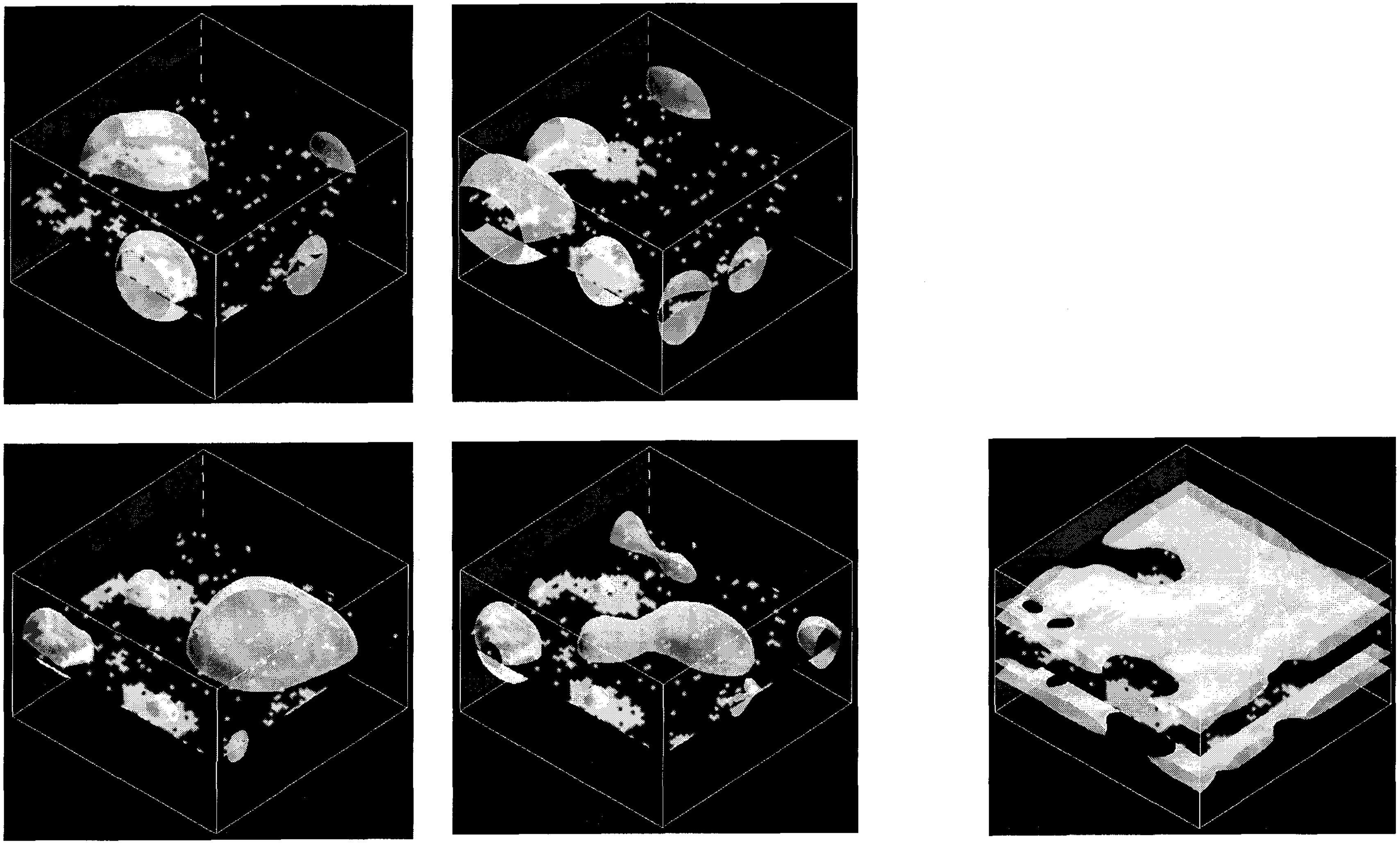


Effect of Island Size on Lower Level

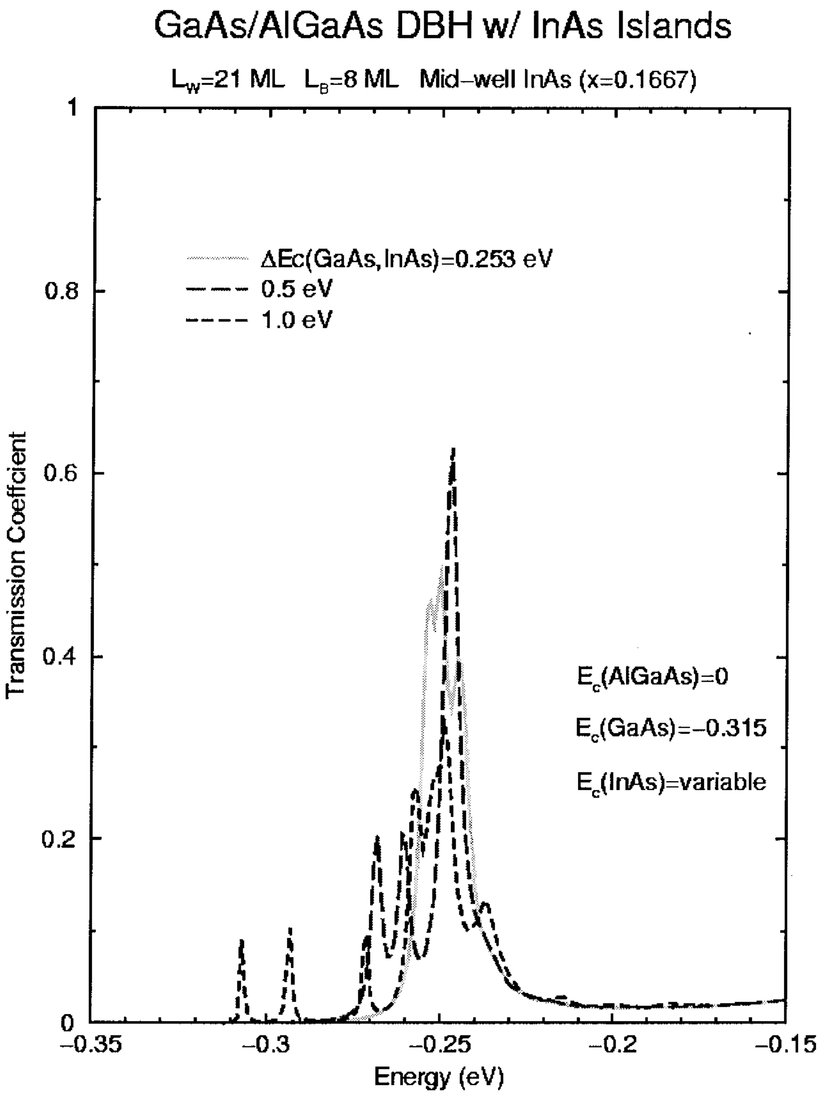


- Increasing down shift and broadening as inserted InAs island size increase
- Peaks splitting in large-island configurations correspond to multiple localized modes.
- Number of localized modes limited by the number of islands that can fit into the simulation domain: 64nm x 64nm x 116 nm.
- Actual detector pixel would have much larger area with a larger ensemble of island configurations.

Resonance Wave Function in λ = 15.7 nm Structure



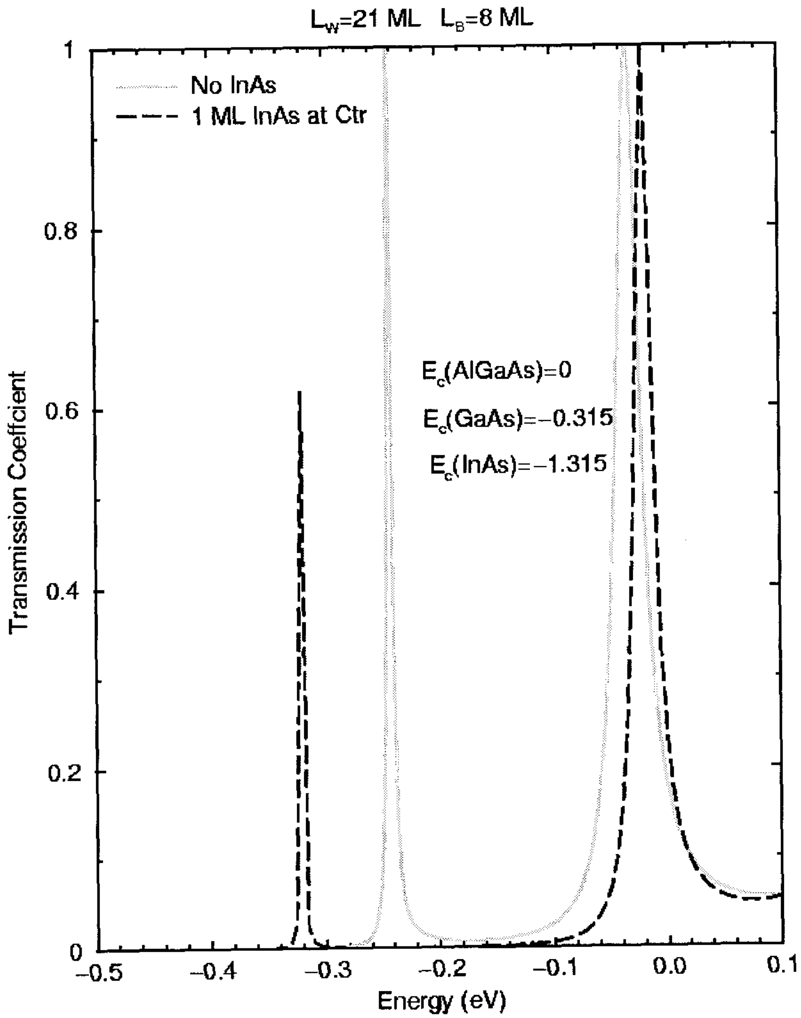
Dependence on Band Offset



- Lower level dependence on band offset.
- ΔE_C(GaAs,InAs) = 0.253, 0.5, 1.0 eV
- Increasing band offset results in larger number of localized states, more widely dispersed.

Full-Monolayer InAs Insert (Large band Offset)

GaAs/AlGaAs DBH w/ InAs Insertion



- Insertion of one full monolayer of InAs, large band offset (1 eV), pulls lower level just below GaAs band edge.

Island Insertion Infrared Detectors: Status

- Prototype device structure grown and tested.
  - Inconclusive results. Higher responsivity, but no significant increase in normal incidence absorption.
  - Growth issues: Less mid-well InAs incorporation due to evaporation or surfactant effect.
- Must optimize growth conditions for island formation.
  - Help from growth modeling ? (Please !)
- Alternatives
  - AlAs islands at step edges at mid-well ?
  - Mid-well Delta doping ?
- More detailed modeling
  - Eigensolvers (Ming Gu)
  - Optical calculations

Summary

- Wave functions of states involved in optical transition engineered to contain lateral variations for absorption of normal incidence radiation.
- Similar to QWIPs in growth and processing.
- Further theoretical and experimental investigations.